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Laser PM to AM Conversion in Atomic Vapors and Short Term Clock Stability

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~~Col. C. Whited~~ J. W. COLE, MAJ, USAF
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The optical thick vapors employed in gas-cell atomic clocks provide for very efficient conversion of laser phase noise)PM) to amplitude noise (AM). Here, we discuss the role of PM to AM conversion in determining gas-cell clock performance. First, a brief overview of the PM to AM conversion process will be given, highlighting the fact that laser phase noise creates fluctuations in the atom's optical absorption cross section, which have an exponential influence on the laser's transmitted intensity. Experimental results will then be presented showing that the PM to AM conversion process can increase the relative intensity noise of transmitted laser light by orders of magnitude, and that this can, under certain conditions, cause laser-pumped clock performance to be poorer than lamp-pumped clock performance.

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Introduction

An important motivation for diode laser optical pumping in the gas-cell atomic frequency standard is the creation of a low power clock of ultraminiature proportions [1]. Not only will such a clock have application in hand-held devices, but due to very efficient optical pumping the ultraminiature laser-pumped clock should have performance characteristics greatly exceeding those of present day lamp-pumped clocks [2,3]. Unfortunately, there are two design features of the ultraminiature laser-pumped clock that constrain this vision. First, the clock's resonance cell by definition must have an ultraminiature length. Consequently, in order to generate absorption signals with a reasonable size over the short path length the alkali vapor density must be high. High alkali vapor density yields high spin-exchange rates, which broaden the clock transition [4]. Additionally, and perhaps more importantly, the optically thick vapor provides for the very efficient conversion of laser phase noise (PM) to amplitude noise (AM), thereby degrading the clock's signal-to-noise ratio [5].

Here we discuss PM to AM conversion in optically thick vapors, and its role in determining gas-cell clock performance. First, a brief overview of the PM to AM conversion process will be given, highlighting the fact that it is *not* a passive feature of optical propagation through a resonant medium. Rather, laser phase noise creates fluctuations in the atom's complex polarizability (i.e., optical absorption cross-section), and these have an exponential influence on the laser's transmitted intensity noise. Experimental results will be presented showing that the PM to AM conversion process can increase the relative intensity noise of transmitted laser light by orders of magnitude, and that this can, under certain conditions, cause laser-pumped clock performance to be poorer than lamp-pumped clock performance. The paper concludes with a discussion of one potential means of mitigating PM to AM conversion in laser-pumped gas-cell clocks.

Origin of PM to AM Conversion

The optical intensity of a light beam transmitted through a resonant vapor, I(z), is typically described in terms of an exponential attenuation law credited to Bouguer, Lambert and Beer [6]:

$$I(z) = I_o \exp(-[N]\sigma z). \tag{1}$$

Here, I_o is the incident intensity, [N] is the number density of absorbing atoms, σ is the absorption cross-section and z is the depth in the absorbing medium. However, for the present purposes it is better to consider the attenuation law as a consequence Maxwell's equations, where it is rephrased as [7]

$$I(z) = I_o \exp\left(-\frac{4\pi k}{n^2} \int_0^z |\chi''| \, dz' \right). \tag{2}$$

In Eq. (2) k is the wavevector of the light, n is the (real) refractive index of the medium, and χ" is the imaginary part of the medium's electric susceptibility.

For the purposes of the present discussion, it is important to note that in general χ is not a fixed constant of the medium, but depends on the field-atom interaction. Specifically, χ can be related to the off-diagonal (i.e.,

coherence) elements of the atomic density matrix, ρ. To illustrate this, note that if P(z) is the electric polarization in the medium at z and $\langle\mu(z)\rangle$ is the expectation value of the electric dipole moment at z, then

$$[N]\langle\mu(z)\rangle \;=\; P(z) \;=\; \mathrm{Re}\left[\chi^{*}(z)\,\varepsilon(z)\right], \quad (3)$$

where $\varepsilon(z)$ is the complex field amplitude:

$$\varepsilon(z) \;=\; E_o(z)\, e^{i\omega t}, \quad (4)$$

and where

$$\langle\mu(z,t)\rangle \;=\; \mathrm{Tr}\left[\rho(z,t)\mu\right] \;=\; 2\mu_o\, \mathrm{Re}\left[\rho_{ge}(z,t)\right]. \quad (5)$$

In Eq. (5), ρ_{ge} essentially describes the ground state and excited state superposition created by the field, and μ_o is the atomic dipole moment associated with the $|g\rangle \rightarrow |e\rangle$ transition (which is a fixed constant for a particular transition [8]). Generally, ρ_{ge} can be written as the product of a slowly varying term, σ_{ge}, and a term rapidly oscillating at the field frequency:

$$\rho_{ge}(z) \;=\; \sigma_{ge}(z)\, e^{-i\omega t}. \quad (6)$$

Consequently, Eqs. (3) through (5) may be manipulated to yield

$$\chi'(z) \;=\; \frac{2[N]\mu_o}{E_o(z)}\, \mathrm{Re}\left[\sigma_{ge}(z)\right]. \quad (7a)$$

$$\chi''(z) \;=\; \frac{2[N]\mu_o}{E_o(z)}\, \mathrm{Im}\left[\sigma_{ge}(z)\right]. \quad (7b)$$

Equation (7b) clearly shows the relationship between the parameter controlling exponential attenuation of light intensity, χ", and the field-atom interaction as manifested in the density matrix coherence term σ_{ge}.

In the case of a weak, monochromatic field (weak in the sense that saturation of the $|g\rangle \rightarrow |e\rangle$ transition can be ignored and that optical pumping effects are minimal), $\sigma_{ge}(z) \sim E_o(z)$, and χ" is a constant that may be removed from under the integral sign of Eq. (2). The intensity attenuation law obtained from Maxwell's equations is then equivalent to the Bouguer-Lambert-Beer exponential attenuation equation. However, if optical pumping affects the population distribution of the atoms in the absorbing medium, then χ" will depend on z, and a more complicated intensity attenuation results.

More importantly for the present discussion, if the laser is not monochromatic, then laser phase fluctuations will induce random variations in σ_{ge} [9]. As is clear from Eq. (7b), the laser-induced fluctuations in the atomic coherence will drive stochastic variations in χ", and hence stochastic variations in optical attenuation. In this way, the absorbing medium converts laser phase fluctuations (PM) into laser intensity fluctuations (AM) [5]. Moreover, as illustrated in Fig. 1 this process is nonlinear, so that in an optically thick vapor the conversion of PM to AM can increase an optical beam's relative intensity noise by orders of magnitude.

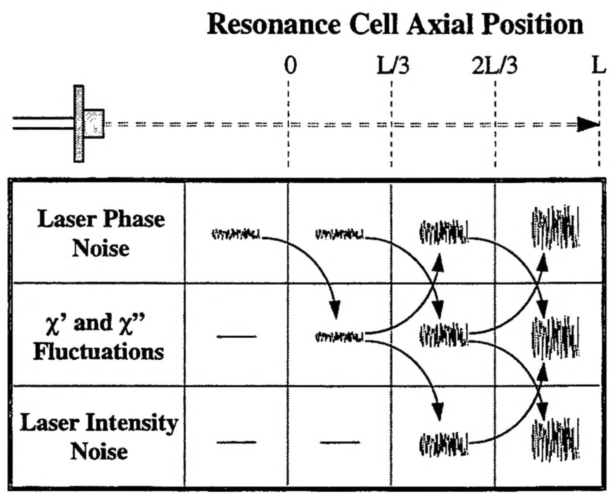

Figure 1: Illustration of how laser phase noise results in transmitted laser intensity noise. Initially, laser phase fluctuations induce fluctuations in the real and imaginary components of the absorbing medium's electric susceptibility. These in turn create fluctuations of the laser phase and intensity inside the absorbing medium. As the laser beam propagates through the vapor the effects multiply. In this paper we ignore the increase in laser phase noise as it propagates through the vapor, and concentrate on the transmitted laser intensity noise.

It should be noted that the PM to AM conversion process is not a passive feature of the absorbing medium. It would be incorrect to think of the vapor as having some frequency dependent transmission function, like a filter, and that laser frequency (i.e., phase) fluctuations alter the detuning between the field and the transmission function's center. Rather, the PM to AM conversion process is an active feature of the field-atom interaction, since it is fundamentally related to field induced fluctuations in the atomic coherence. We also note that while PM to AM conversion is an unwanted noise source for our purposes, it has application as a spectroscopic tool [10].

Magnitude of PM to AM Conversion

Figure 2 is a block diagram of an experiment that we performed to investigate the magnitude of PM to AM conversion in a laser-pumped gas-cell clock system [5]. A Mitsubishi diode laser with a linewidth of 60 MHz was tuned to the D_1 transition of Rb^{87} at 794.7 nm (i.e., $5^2S_{1/2}(F=2) \rightarrow 5^2P_{1/2}$). The pure Rb^{87} vapor was contained in a cylindrical Pyrex resonance cell along with ten torr of N_2. The resonance cell length was 3.5 cm and its diameter was 2.5 cm. The relative intensity noise, RIN, was defined as the ratio of the average laser intensity (measured with a lock-in amplifier) to the low frequency noise amplitude in a one hertz bandwidth (measured with a spectrum analyzer). The RIN of the laser was measured prior to passage through the resonance cell and after passage.

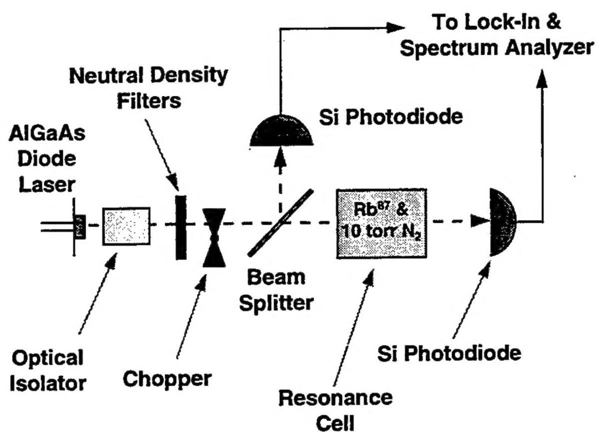

Figure 2: Experimental arrangement that was used to demonstrate the PM to AM conversion process and determine its magnitude in an atomic clock system.

Figure 3 shows the results of the experiment: laser RIN versus laser intensity. The laser RIN was measured at a Fourier frequency of 209 Hz, corresponding to a typical modulation frequency used in the gas-cell atomic clock. Circles correspond to the laser RIN after passage through the resonance cell, and with the laser tuned on resonance. Diamonds correspond to the laser RIN prior to passage through the resonance cell, or after passage but with the laser tuned *off* resonance. At low light intensities propagation through an optically thick vapor yields a nearly two orders of magnitude increase in laser RIN. Note, though, that at high light intensities this enhancement of RIN can be mitigated.

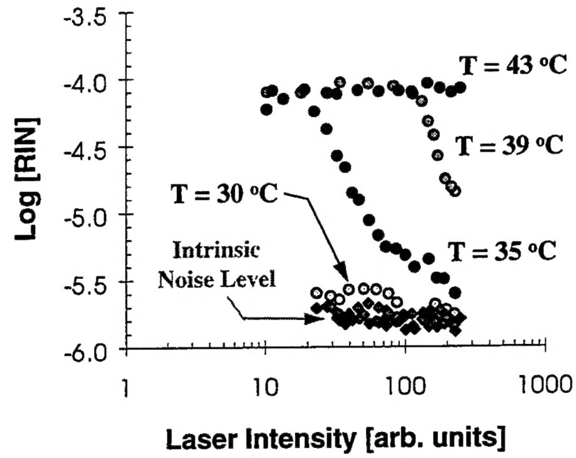

Figure 3: Results of experiment to demonstrate the magnitude of PM to AM conversion in a gas-cell atomic clock system. Note that if the laser RIN was shot-noise limited, the data would show Log[RIN] ~ -½ Log[I].

The decrease in laser RIN with intensity is a consequence of optical pumping. At high light intensities optical pumping is very efficient, and the number of atoms in the absorbing state is reduced. Consequently, even though the (total) number density of vapor phase atoms is high, the vapor is optically thin, and the PM to AM conversion process is therefore inefficient. The intensity where this "optical pumping" decrease in RIN enhancement takes place is a sensitive function of temperature. We believe that this is related to the role of radiation trapping in the optical pumping process [11,12].

Increase of RIN on Propagation

As indicated by Fig. 1, a hallmark of the PM to AM conversion process is its increase upon propagation through a resonant vapor. This was demonstrated with an experimental arrangement similar to Fig. 2, but monitoring laser induced fluorescence (LIF) with an avalanche photodiode (APD) as opposed to laser transmission. The resonance cell temperature was set to 50°C, and the LIF from the entrance, middle, and exit of the resonance cell was imaged on the APD. The resonance cell was similar in design to the one used in the previous experiment except that it was filled with natural Rb and 14 torr of Ne as a buffer gas so as not to quench the atomic fluorescence. Figure 4 shows the results of that experiment with relative noise defined as the ratio of noise amplitude at 200 Hz (in a one hertz bandwidth) to the square root of the average LIF signal. Consistent with the PM to AM conversion model, the laser intensity noise showed a 22% increase on propagation through the vapor for our experimental conditions.

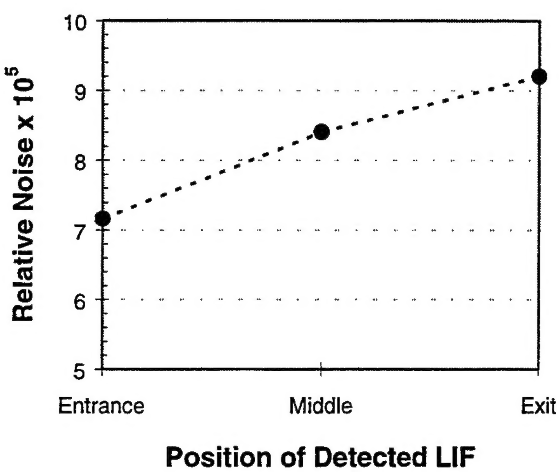

Figure 4: Results of experiment to demonstrate increase of laser RIN on propagation through a resonant alkali vapor.

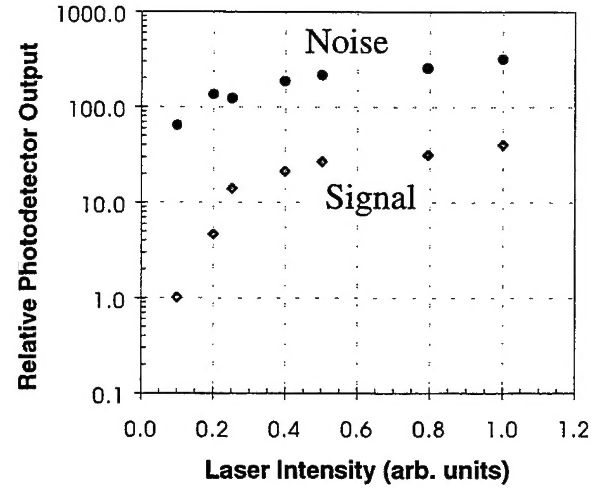

Figure 5: Results of an experiment to investigate the influence of PM to AM conversion on laser-pumped clock performance. The noise voltage and signal voltage as measured by the clock's photodetector are relative to the values these parameters had under normal lamp-pumping.

PM to AM Conversion and Clock Performance

In order to assess the significance of PM to AM conversion on laser-pumped gas-cell clock performance, we measured the clock signal level and noise level in a commercial Rb atomic clock. Essentially, we replaced the Rb rf-discharge lamp with our diode laser in a commercial Rb clock that we had modified for our experimental purposes. We swept the clock's microwave frequency across the alkali hyperfine transition in order to measure the clock signal amplitude, and then tuned the microwave frequency to resonance and measured the clock signal's noise level. The clock signal and noise were measured via the clock's internal photodetector. Microwave power and resonance cell temperature where kept at their nominal (i.e., lamp) operating values.

The experimental results are shown in Fig. 5, where the laser-pumped clock's signal level and noise level are plotted as a function of input laser intensity. The signal level and noise level are shown relative to the values measured for the lamp-pumped clock. As expected, optical pumping with the laser increased the clock signal by more than an order of magnitude over what could be attained with lamp optical pumping. However, under the clock's nominal operating conditions the noise level was also increased, and by more than two orders of magnitude due to efficient laser PM to AM conversion. Consequently, for these experimental conditions the laser-pumped clock's signal-to-noise ratio would be poorer than the lamp-pumped clock's signal-to-noise ratio.

We wish to emphasize that the results shown in Fig. 5 *do not* imply that laser optical pumping in the gas-cell clock is worse than lamp optical pumping as a general matter. As demonstrated by Mileti et al. [13] this is certainly not the case. Rather, the results of Fig. 5 should be seen as cautionary with regards to the simple replacement of a lamp with a diode laser in a gas-cell clock. Apparently, PM to AM conversion in the laser-pumped clock has a more deleterious influence on stability than it does in a lamp-pumped clock. Consequently, as pointed out by Mileti et al. [13], in order to achieve the ultimate in short-term performance from a laser-pumped gas-cell clock one must work to reduce the influence of PM to AM conversion on the clock's signal-to-noise ratio.

Mitigating PM to AM Conversion

The efficiency of PM to AM conversion in a laser-pumped, gas-cell clock depends on at least three parameters: the laser linewidth, the vapor's optical depth, and the degree of optical pumping. Laser linewidth affects the conversion efficiency because the linewidth is proportional to the variance of phase fluctuations [14], and the greater the initial PM, the greater the converted AM. Optical depth plays a role because efficient conversion requires non-negligible absorption. Since the optical depth of a vapor is related to the number density of atoms in the absorbing state, and since this is controlled by optical pumping, the degree of optical pumping enters as a parameter controlling the PM to AM conversion efficiency.

Though it should be possible to mitigate PM to AM conversion on atomic clock performance through one or all of these parameters, achieving that mitigation may not be trivial. Clearly, laser pumping in the clock is best performed with a narrow linewidth diode laser. However, constraints on overall clock size and clock operating power could force the use of diode lasers with linewidths that are not optimal from a PM to AM conversion perspective. Additionally, the relationship of optical pumping to clock performance in the presence of PM to AM conversion is fairly complicated. For example, on the one hand clock signal is increased by optically pumping all atoms from one hyperfine manifold into the $m_F=0$ Zeeman sublevel of the other manifold. However, upon resonant interaction with the microwaves a large fraction of these atoms return to the absorbing $m_F=0$ state and give rise to efficient PM to AM conversion. Alternatively, if a large fraction of the atoms optically pumped from one manifold into the other reside in Zeeman sublevels with $m_F \neq 0$, then fewer atoms will be returned to the absorbing state upon resonant interaction with the microwaves, and hence there will be reduced PM to AM conversion; of course there will also be a reduced clock signal under such conditions. Finally, if a clock signal is generated via laser transmission through the vapor, then one is constrained to work with optically thick vapors (i.e., $[N]\sigma L \sim 2\text{-}4$).

One means of mitigating, though perhaps not eliminating, PM to AM conversion is through LIF detection of clock signals. As a consequence of spatial diffusion, the degree of optical pumping in a gas-cell clock is not uniform along the length of the vapor. The population imbalance between the two alkali $m_F=0$ sublevels is zero at the entrance and exit of the resonance cell, and reaches a maximum somewhere near the middle of the resonance cell [15]. When this fact is coupled with the observation that PM to AM conversion increases upon propagation, one would conclude that there must be some optimal axial position associated with the clock's signal to noise ratio (i.e., an axial position where optical pumping and hence clock signal is large, but PM to AM conversion is relatively small). This optimal axial position could be accessed by imaging the region onto an APD, and detecting the clock transition as an LIF signal.

As a first step in exploring the utility of an LIF gas-cell clock, we imaged the entire length of our natural Rb/Ne resonance cell onto an APD, and measured the clock signal amplitude, S, linewidth, $\Delta\nu$, and noise level, N, in order to estimate the Allan standard deviation [16]:

$$\sigma_y(\tau) \cong \frac{0.2\Delta\nu}{\nu_o\left(S/N\right)}\frac{1}{\sqrt{\tau}} \quad . \tag{8}$$

Here, ν_o is the Rb^{87} ground state hyperfine splitting. (Note that we did not infer shot noise, but measured the noise in a one hertz bandwidth with a spectrum analyzer at 200 Hz.) The estimated Allan standard deviation as a function of resonance cell temperature is shown in Fig. 6. At low temperature, there was little fluorescence due to the low alkali vapor density, and hence the clock signal was small. At higher temperatures PM to AM conversion contributed significantly to the noise level. The point to note is that without any optimization as to light collection geometry, the estimated Allan standard deviation reached 10^{-12} levels. (We did perform a rudimentary optimization with regard to light intensity and microwave power.) Consequently, LIF detection with an APD is a viable means of clock signal detection, and its potential for axial position discrimination may reduce the influence of PM to AM conversion on laser-pumped, gas-cell clock performance.

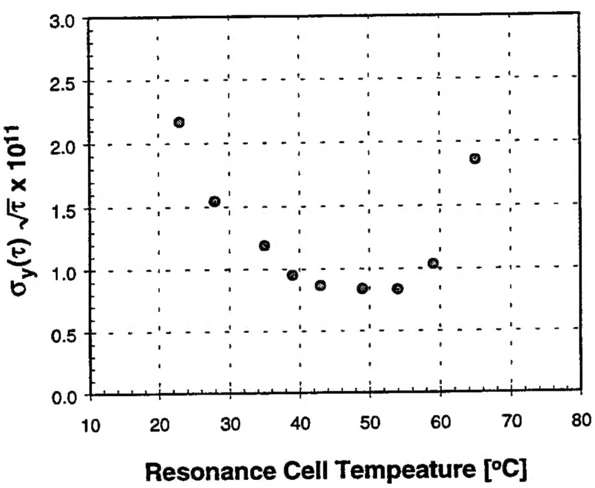

Figure 6: Estimated Allan standard deviation as a function of resonance cell temperature for an LIF clock signal.

Conclusions

In this paper we have discussed the role of PM to AM conversion in determining gas-cell clock performance. Following a brief overview of the PM to AM conversion process, where it was noted that the conversion process should *not* be viewed as a passive feature of the absorbing medium, experimental results were presented showing that the converted AM noise has the potential to seriously degrade laser-pumped gas-cell clock performance. One method of mitigating PM to AM

conversion is to employ very narrow linewidth diode lasers for optical pumping. A complimentary strategy outlined here employs LIF detection of gas-cell clock signals. Basically, since PM to AM conversion increases on propagation through an absorbing medium, it should be possible to image an axial region on an APD that has relatively large signal amplitude but relatively low PM to AM conversion noise. We intend to continue our investigations into mitigating strategies for PM to AM conversion, and in particular to examine the role of radiation trapping in the optical pumping process and how this influences PM to AM conversion.

References

1. See for example: P. J. Chantry, I. Liberman, W. R. Verbanets, C. F. Petronio, R. L. Cather, and W. D. Partlow, "Miniature laser-pumped cesium cell atomic clock oscillator," in Proc. 1996 IEEE Intrl. Freq. Control. Sym. (IEEE, Catalog #96CH35935,1996) pp. 1002-1010.

2. J. C. Camparo and R. P. Frueholz, "Fundamental stability limits for the diode-laser-pumped rubidium atomic frequency standard," J. Appl. Phys. 59(10), 3313 (1986).

3. J. C. Camparo and R. P. Frueholz, "A comparison of various alkali gas-cell atomic frequency standards," Trans. Ultrason. Ferroelec. and Freq. Control UFFC-34(6), 607 (1987).

4. W. Happer, "Optical pumping," Rev. Mod. Phys. 44(2), 169 (1972).

5. J. C. Camparo, "Conversion of laser phase noise to amplitude noise in an optically thick vapor," submitted to J. Opt. Soc. Am. B.

6. H. G. Pfeiffer and H. A. Liebhafsky, "The origins of Beer's law," J. Chem. Educ. 28, 123 (1951); I. Botev, "A new conception of Bouguer-Lambert-Beer's law," Fresenius Z. Anal. Chem. 297, 419 (1979).

7. P. Meystre and M. Sargent III, *Elements of Quantum Optics* (Springer-Verlag, Berlin, 1991) Ch. 1.

8. R. C. Hilborn, "Einstein coefficients, cross sections, f values, dipole moments, and all that," Am. J. Phys. 50(11), 982 (1982), and Am. J. Phys. 51(3), 471 (1983).

9. See: J. C. Camparo and P. Lambropoulos, "Monte Carlo simulation of field fluctuations in strongly driven resonant transitions," Phys. Rev. A 47(1), 480 (1993), and references therein.

10. R. Walser, J. Cooper, and P. Zoller, "Saturated absorption spectroscopy using diode-laser phase noise," Phys. Rev. A 50(5), 4303 (1994), and references therein.

11. For a good discussion of recent developments in radiation trapping see: A. F. Molisch, B. P. Oehry, and G. Magerl, "Radiation-trapping in a plane-parallel slab," J. Quant. Spectrosc. Radiat. Transfer 48(4), 377 (1992).

12. A. F. Molisch, W. Schupita, B. P. Oehry, B. Sumetsberger, and G. Magerl, "Modeling and efficient computation of nonlinear radiation trapping in three-level atomic vapors," Phys. Rev. A 51(5), 3576 (1995).

13. G. Mileti, J. Q. Deng, F. L. Walls, J. P. Lowe, and R. E. Drullinger, "Recent progress in laser-pumped rubidium gas-cell frequency standards," in Proc. 1996 IEEE Int. Freq. Contr. Symp. (IEEE, Catalog #96CH35935,1996) pp. 1066-1072.

14. S. F. Jacobs, "How monochromatic is laser light?," Am. J. Phys. 47(7), 597 (1979).

15. J. C. Camparo and R. P. Frueholz, "A nonempirical model of the gas-cell atomic frequency standard," J. Appl. Phys. 59(2), 301 (1986).

16. J. Vanier and L.-G. Bernier, "On the signal-to-noise ratio and short-term stability of passive rubidium frequency standards," IEEE Trans. Instrum. Meas. IM-30(4), 277 (1981).

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